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(71) Applicant: RAYTHEON COMPANY [US/US]; 141 Spring Street, Lexington, MA 02421 (US).

(72) Inventors: CHANDRA, Dipankar; 1404 Baltimore, Richardson, TX 75081 (US). SYLLAIOS, Athanasios, J.; 12 Bunker Hill, Richardson, TX 75080 (US).

(74) Agent: MILLS, Jerry, W.; Baker & Botts, L.L.P., 2001 Ross Avenue, Dallas, TX 75201-2980 (US).

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(54) Title: SENSOR FOR DETECTING SMALL CONCENTRATIONS OF A TARGET MATTER

(57) Abstract

A gas sensor is constructed to detect and measure concentrations of a target matter in either a microenvironment or in normal applications. A piezoresistive layer is mechanically coupled to a chemical sensitive layer. The reaction of the target matter with the chemical sensitive layer creates an induced strain in the chemical sensitive layer. This induced strain in the chemical sensitive layer in turn causes stress to be applied to the piezoresistive material. The applied stress results in a change in resistance of the piezoresistive material. This change in resistance is a measure of the concentration of the target matter that is interacting with the chemical sensitive layer.

SENSOR FOR DETECTING SMALL CONCENTRATIONS OF A TARGET MATTER

TECHNICAL FIELD OF THE INVENTION

This invention relates generally to gas and chemical sensors and more particularly to a micro-electromechanical system for detecting very small concentrations of a target matter.

BACKGROUND OF THE INVENTION

A multitude of sensors are presently in use to detect various types of gases and chemical compounds. Such sensors range from the common household smoke detector to those designed to detect deadly nerve gases. Many of these applications require sensors that are sensitive and relatively small in size.

Current sensing and detection technologies have a number of drawbacks such as poor sensitivity and selectivity for the target matter, relatively long analysis times, lack of portability, and relatively high costs. For some applications, detection sensitivities in the part per trillion range (ppt) are needed, but few techniques even approach such sensitivity levels. For example, explosive sensors must be able to detect target matter such as TNT with below part per billion (ppb) sensitivity. Similarly, chemical agent sensors must exhibit sub-ppb sensitivity and be capable of distinguishing the nerve agent class (GA, GB,

GD, GF, VX) and the blistering agent class (HD, L, T) of chemical agents. Present sensor technology generally does not offer the capability of sensing concentrations below the ppb range.

SUMMARY OF THE INVENTION

Accordingly, a need has arisen for a compact, light weight, low power, high sensitivity sensor capable of detecting chemical concentrations in gas and liquid phases with sub-ppb sensitivity. The present invention provides a sensor that addresses these needs.

According to one aspect of the present invention, a gas sensor is constructed to detect and measure concentrations of a target matter in either a microenvironment or in normal applications. Preferably, a piezoresistive layer is mechanically coupled to a selected chemical sensitive layer. The target matter reacts with the chemical sensitive layer and creates an induced strain in the chemical sensitive layer. The chemical sensitive layer is coupled to the piezoresistive material in a manner such that the reaction of the chemical sensitive layer to the target matter (the induced strain) applies stress to the piezoresistive material. This applied stress typically results in a change in resistance of the piezoresistive material. This change is resistance may be used to indicate the concentration of the target matter that is interacting with the chemical sensitive layer.

Embodiments of the invention provide numerous technical advantages. For example, sensors incorporating teachings of the present invention may be manufactured as micro-electromechanical systems (MEMS) for use in both microenvironments and normal environments. In one embodiment of the present invention, a MEMS chemical

sensitive single crystal silicon cantilever design is used which has no moving parts, therefore making the embodiment simple and compact. Another technical advantage is the use of a chemical sensitive layer with selected sensitivity to specific gases, liquids, and chemical species. The use of this chemical sensitive layer in combination with a piezoresistive material allows for sub-ppb sensitivity.

Still further technical advantages of the present invention include the use of a chemical sensitive sensor cantilever and non-chemical sensitive reference cantilever pair to compensate for environmental transients. In addition, one embodiment provides multichannel capability to detect multiple types of gases, liquids or chemical species. Furthermore, sensors incorporating the present invention may be used in outdoor sensor networks and hand-held applications due to their ruggedness, compactness, low weight, low power requirements, and low cost.

Sensors formed in accordance with teachings of the present invention may be used for continuous monitoring of a target matter while remaining unsaturated during the useable lifetime of the sensor. Sensors incorporating teachings of the present invention are also capable of operating as stand alone sensors or as components of networked arrays of diverse sensors.

Other technical advantages are readily apparent to one skilled in the art from the following figures, descriptions, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and the advantages thereof, reference is now made to the following descriptions taken in connection with the accompanying drawings in which:

FIGURE 1 is a schematic drawing in elevation showing a sensor incorporating one embodiment of the present invention;

FIGURE 2 is a schematic drawing showing an isometric view of the sensor of FIGURE 1 and an electrical circuit for obtaining data from the sensor;

FIGURE 3 is a schematic drawing in elevation showing portions of a micro-electromechanical system for detecting very small concentrations of a selected target matter in accordance with teachings of the present invention;

FIGURE 4 is a plan view of a portion of the micro-electromechanical system of FIGURE 3; and

FIGURE 5 is a schematic drawing of a sensing system incorporating another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention and its advantages are best understood by referring to FIGURES 1 through 5 of the drawings, like numerals being used for like and corresponding parts of the various drawings.

The following terms will be used throughout the application. Therefore, their definitions are provided here. In this application, the term "target matter" shall mean a gas, vapor, liquid, chemical species, or any other type of matter which is sought to be detected.

In this application, the term "ppm" shall stand for "part per million". The phrase "part per million" shall mean that for every one million parts of a certain medium

(i.e. air), there is only one part of the target matter. The "part" can be any representative amount of a substance, such as a molecule or a certain volume. Similarly, the terms "ppb" and "ppt" stand for "part per billion" and "part per trillion", respectively. The meaning of these phrases is clear from the meaning of "part per million", discussed above.

Furthermore, in this application, the term "chemical sensitive" shall be used to described a substance that reacts to or is sensitive to a selected target matter. For example, chemical sensitivity of a substance to a particular target matter could cause a strain to be induced in the substance due to the reaction of the substance and the target matter.

FIGURES 1 and 2 show a sensor 10 representing one embodiment of the present invention. This embodiment is simplified to show the three components of the invention and their operation. The first such component includes a layer 20 of a selected piezoresistive type material. Piezoresistive material 20 experiences a change in bulk resistance when stress is applied to it. Piezoresistive material 20 may be layered on or implanted in a support medium 22, or it may stand alone.

The second such component includes a chemical sensitive layer 30. Chemical sensitive layer 30 is mechanically coupled or bonded to piezoresistive material 20. Chemical sensitive layer 30 is comprised of a material chosen to preferentially react with a selected target matter. The interaction of the target matter (not explicitly shown) with chemical sensitive layer 30 may change the physical properties of chemical sensitive layer 30, such as molar volume, morphology, and the like, and may

lead to a microscopic change in the dimensions (strain) of chemical sensitive layer 30.

The target matter may be any existing matter that reacts with a particular type of chemical sensitive layer in this way. The reaction in chemical sensitive layer 30 may be caused by a variety of interactions between chemical sensitive layer 30 and the target matter. These interactions may include, but are not limited to, absorption, adsorption, and amalgamation. In addition, sensor 10 is not limited to detecting concentrations of a target matter dispersed in the air. Sensor 10 can be used to measure a target matter concentration in a multitude of gas, liquid, and multi-phase environments.

Since chemical sensitive layer 30 is coupled to piezoresistive material 20, the strain induced in chemical sensitive layer 30 causes stress to be applied to piezoresistive material 20. This applied stress results in a change in resistance of piezoresistive material 20. This change in resistance may then be measured by the third component, an electrical circuit 40, shown in FIGURE 2.

Chemical sensitive layer 30 is not shown in FIGURE 2 to more clearly show electrical circuit 40. Piezoresistive material 20 is electrically coupled to electrical circuit 40 through a pair of electrical leads 42. Electrical current may naturally flow through piezoresistive material 20, or it can be directed by electrical wiring 44. Any type of electrical circuit capable of detecting and/or measuring a change in resistance may be used in conjunction with piezoresistive material 20 and chemical sensitive layer 30.

It should be noted that the configuration of piezoresistive material 20 and chemical sensitive layer 30 in FIGURE 1 is only one example of many different possible

configurations. Piezoresistive material 20 is not required to cover an entire surface of support medium 22. In fact, such a configuration may not be desired for some applications. Piezoresistive material 20 is preferably placed in selected areas based on the stresses induced by chemical sensitive layer 30 in response to the target material. For instance, piezoresistive material may be placed at locations where the applied stress is expected to be maximized.

Furthermore, chemical sensitive layer 30 does not have to entirely cover piezoresistive material 20. It may also be placed in more than one area to obtain configurations with enhanced sensitivity. In general, piezoresistive material 20 and chemical sensitive layer 30 are placed in relation to each other such that the strain induced in chemical sensitive layer 30 causes a change in resistance in piezoresistive material 20 that can be effectively detected and/or measured and associated with a corresponding concentration of the target matter.

FIGURE 3 shows a sensor 100 representing another embodiment of the present invention. This embodiment may generally be described as a MEMS bulk micromachined piezoresistive cantilever sensor with a chemical sensitive layer. Sensor 100 incorporates the same chemical sensitive/piezoresistive principles as sensor 10, shown in FIGURE 1.

Sensor 100 includes a cantilevered beam 122 mounted on a substrate 124. Substrate 124 may perform at least two different functions. One such function may be to simply provide mechanical support for the cantilevered beam 122. Substrates performing this function may be fabricated from materials such as ceramics, plastics, glass, metals, or semiconductors such as silicon (Si), germanium (Ge),

gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), indium phosphide (InP), cadmium telluride (CdTe), and other Group III-V or II-VI semiconductor compounds. Another function that substrate 124 may perform is hosting electronic circuitry for acquiring and processing signals generated in the sensor. Substrates performing this function may be fabricated from materials such as silicon (Si), germanium (Ge), gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), indium phosphide (InP), cadmium telluride (CdTe), silicon carbide (SiC), and other Group III-V or II-VI semiconductor compounds.

Beam 122 may serve as a support medium for one or more regions 120 of piezoresistive material implanted in beam 122. Piezoresistive regions 120 may comprise any type of piezoresistive material including, but not limited to, silicon doped with boron or phosphorus. However, the beam itself may also be comprised of piezoresistive material. Beam 122 may be made of appropriately doped silicon, Ge, GaAs, AlGaAs, SiC, diamond films, and conductive polymers such as polyimide/graphite composites.

A chemical sensitive layer 130 is coupled or bonded to piezoresistive layer 120. As described above in relation to FIGURE 1, chemical sensitive layer 130 comprises a material specifically chosen to preferentially react with a target matter. Beam 122 bends as a result of the stress induced by the chemical sensitive layer when exposed to the target matter. As beam 122 bends, the resistance of piezoresistive layer 120 is changed. This change in resistance can then be detected and/or measured using an electrical circuit (not explicitly shown). This electrical circuit is coupled to piezoresistive layer 120 through the use of one or more bonding pads 140. Bonding pads 140 are used to support the wires of the electric circuit, and to

maintain the connection of these wires to piezoresistive layer 120. Evaporated metals with low electrical conductivity may be used as bonding pads 140.

As shown in FIGURE 4, a double beam cantilever shape may be employed that has two legs 123a and 123b. In this configuration, an electrical current directed into leg 123a will flow out of leg 123b, or the reverse. This current flow is used to measure the change in resistance of piezoresistive layer 120, and thus measure the concentration of the target matter. It should be noted that this "U"-shaped configuration is not required. The electrical current may be directed by other geometrical configurations, or the current by be conducted through the use of electrical wiring.

FIGURE 5 shows a sensing system 200 incorporating teachings of the present invention. Sensing system 200 comprises two cantilevered beams. One beam is a signal beam 210 and the other is a reference beam 220. As shown in FIGURE 5, beams 210 and 220 are "U"-shaped double cantilever beams, however, any type of beam or membrane supported in any way could also be used. As described above, the "U"-shaped beam may be used so that electrical current directed into one leg 123a of the "U" will flow out of the other leg 123b.

Signal beam 210 comprises one or more piezoresistive regions (not explicitly shown) and a chemical sensitive layer (not explicitly shown). However, reference beam 220 does not include a chemical sensitive layer. Reference beam 220 does includes one or more piezoresistive regions (not explicitly shown).

Signal beam 210 and reference beam 220 are preferably coupled to an electrical circuit 230 through the use of bonding pads 140, as shown in FIGURE 5. Electrical circuit

230 is used to detect and/or measure the change in resistance of the piezoresistive material of signal beam 210. Through the use of electrical circuit 230, the output of signal beam 210 is referenced to the output of reference beam 220. The use of a signal/reference pair eliminates system drift due to changes in ambient conditions in the monitoring environment. These ambient conditions include, but are not limited to, temperature, humidity, vibration, and the deposition of nontarget matter.

In the embodiment shown in FIGURE 5, electrical circuit 230 comprises a Wheatstone bridge to measure the resistance change of signal beam 210. The configuration of a Wheatstone bridge is well known in the art, so it will not be described in detail here. The Wheatstone bridge includes four main sources of resistance. These sources of resistance are two resistors 232, signal beam 210, and reference beam 220. Signal beam 210 is connected in one arm of the Wheatstone bridge, and reference beam 220 is connected in another arm of the bridge. Electrical circuit 230 also includes a voltage source 234.

The change in resistance of the piezoresistive material of signal beam 210 is determined by measuring the output voltage of electrical circuit 230. Connecting reference beam 220 as one of the resistors eliminates common mode noise and interfering effects, and provides for an accurate measurement of the change in resistance of the piezoresistive material of signal beam 210.

The output voltage is amplified using an amplifier 236. The amplified voltage reading is then sent, via an interface 240, to a digital or analog output device. Examples of such devices are a digital signal processor 242, a central processing unit 244, and an analog output device 246. The analog or digital output device may

include a database that correlates a measured voltage or change in resistance with a certain concentration of the target matter. The analog or digital output device may then display or transmit the measured concentration to a user.

Embodiments of the present invention may be used as dosimeters to measure the total exposure to a target matter, as well as being used as detectors. By integrating the signal response over time, the total amount of the target matter that reacts with a chemical sensitive layer in that time interval can be determined.

Furthermore, it should be understood that the present invention may be used as a continuous monitoring detector to measure a change in the concentration of a target matter. Although the reaction of the target matter with the chemical sensitive layer is not, in general, a reversible process, additional exposure can be measured as long as saturation of the chemical sensitive layer is not reached. In this continuous monitoring mode, a detector incorporating teachings of the present invention may make continuous samples over successive time intervals of a user-specified duration. The incremental change in resistance of the piezoresistive material is measured over the time interval. The output may then be specified in terms of a change in the target matter concentration over each time interval or as a total dose measurement by integrating the response over an extended period of time. A system incorporating the present invention is capable of detecting changes in concentration in the ppt range.

For a given chemical sensitive layer thickness, saturation is proportional to the product of the target matter concentration and the exposure time. That is to say, saturation is achieved when the chemical sensitive

layer is fully reacted with the target matter, and no more target matter can be absorbed. Hence, as the ambient target matter concentration is decreased, the exposure time required for saturation increases. For example, a MEMS chemical sensitive cantilever detector exposed to ambient target matter concentrations at the ppb level will last one thousand times longer than when exposed to target matter concentrations at the ppm level.

In addition, sensors representing an embodiment of the present invention may be arranged in a multichannel functional array (not explicitly shown). Such an array allows each individual sensor to have maximum sensitivity to a precise target matter. In this manner, an array may be used to detect a variety of different target matters. For example, an array could be used to detect a variety of different types of explosives and chemical weapon agents.

The present invention can theoretically be used to detect any type of target matter. The only requirement is that the chemical sensitive layer react with the target matter so as to apply a stress to the piezoresistive material. The MEMS chemical sensitive cantilever detector, shown in FIGURES 3 and 4, has been used to demonstrate detection of mercury (Hg) vapor and volatile organic compounds (VOCs) such as alcohols, acetone, and benzene with sub-ppb sensitivity. In the case of Hg detection, the chemical sensitive layer used can be a 1000 Å Au film. In the case of VOC detection, photoresist can be used as the chemical sensitive layer.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alterations can be made therein without departing from the spirit and scope of the present invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A sensor for detecting a target matter, the sensor comprising:

a chemical sensitive layer operable to react when exposed to the target matter;

a piezoresistive material coupled to the chemical sensitive layer; and

an electrical circuit coupled to the piezoresistive material operable to detect a change in the electrical resistance of the piezoresistive material.

2. The sensor of Claim 1, wherein the electrical circuit is further operable to measure the change in the electrical resistance of the piezoresistive material.

3. The sensor of Claim 1, further comprising the piezoresistive material coupled to the chemical sensitive layer such that reaction of the chemical sensitive layer with the target matter operates to apply stress to the piezoresistive material.

4. The sensor of Claim 1, further comprising the piezoresistive material coupled to the chemical sensitive layer such that an induced strain in the chemical sensitive layer results in stress being applied to the piezoresistive material.

5. The sensor of Claim 1, wherein the chemical sensitive layer comprises a material that undergoes an induced strain when exposed to the target matter.

6. The sensor of Claim 1, wherein the chemical sensitive layer comprises a material whose dimensions are microscopically changed when exposed to the target matter.

7. The sensor of Claim 1, wherein the electrical circuit comprises a Wheatstone bridge.

8. The sensor of Claim 1, wherein the target matter comprises mercury and the chemical sensitive layer comprises gold.

9. The sensor of Claim 1, wherein the target matter comprises a volatile organic compound and the chemical sensitive layer comprises photoresist..

10. A sensor for detecting a target matter, the sensor comprising:

a cantilevered beam having one or more piezoresistive regions disposed thereon;

each piezoresistive region comprising a piezoresistive material having an electrical resistance;

a chemical sensitive layer coupled to at least one of the piezoresistive regions;

the chemical sensitive layer formed from material that reacts when exposed to the target matter; and

an electrical circuit coupled to at least one of the piezoresistive regions operable to detect a change in the electrical resistance of the piezoresistive material.

11. The sensor of Claim 10, wherein the electrical circuit is further operable to measure the change in the electrical resistance of the piezoresistive material.

12. The sensor of Claim 10, wherein the cantilevered beam comprises a generally "U"-shaped double beam configuration.

13. The sensor of Claim 10, further comprising the chemical sensitive layer coupled to the cantilevered beam such that reaction of the chemical sensitive layer with the target matter operates to cause deflection of the cantilevered beam.

14. The sensor of Claim 13, further comprising each piezoresistive region located on the cantilevered beam such that deflection of the cantilevered beam causes stress to be applied to at least one piezoresistive region.

15. The sensor of Claim 10, further comprising a second beam having at least one piezoresistive region coupled to the electrical circuit in such a manner as to eliminate common mode noise and interfering effects.

16. The sensor of Claim 10, wherein the electrical circuit comprises a Wheatstone bridge.

17. A method of detecting a target matter comprising:

forming a chemical sensitive layer of material selected to react when exposed to the target matter;

coupling the chemical sensitive layer to a piezoresistive material in a manner such that the reaction of the chemical sensitive layer to the target matter applies stress to the piezoresistive material;

exposing the chemical sensitive layer to the target matter; and

detecting a change in the electrical resistance of the piezoresistive material in response to the application of stress by the chemical sensitive layer.

18. The method of Claim 17, further comprising measuring a change in the electrical resistance of the piezoresistive material in response to the application of stress by the chemical sensitive layer.

19. The method of Claim 17, further comprising correlating the measured change in resistance of the piezoresistive material with a corresponding concentration of the target matter.

20. The method of Claim 17, wherein reaction of the chemical sensitive layer with the target matter comprises an induced strain in the chemical sensitive layer.

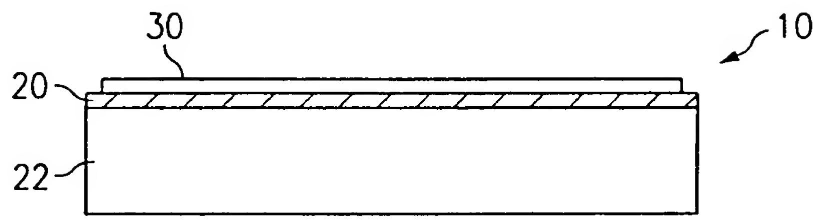


FIG. 1

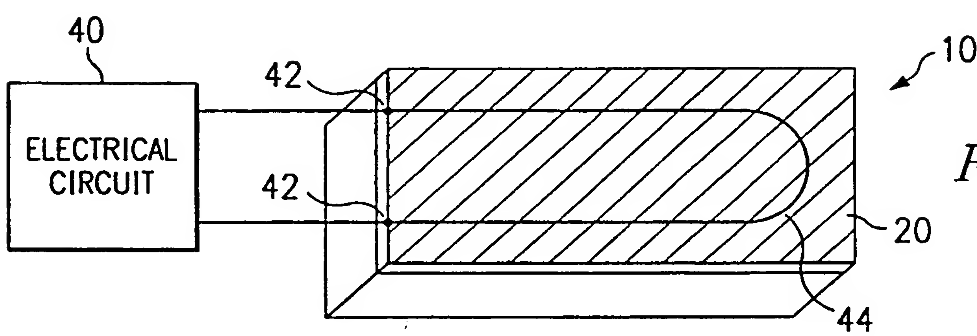


FIG. 2

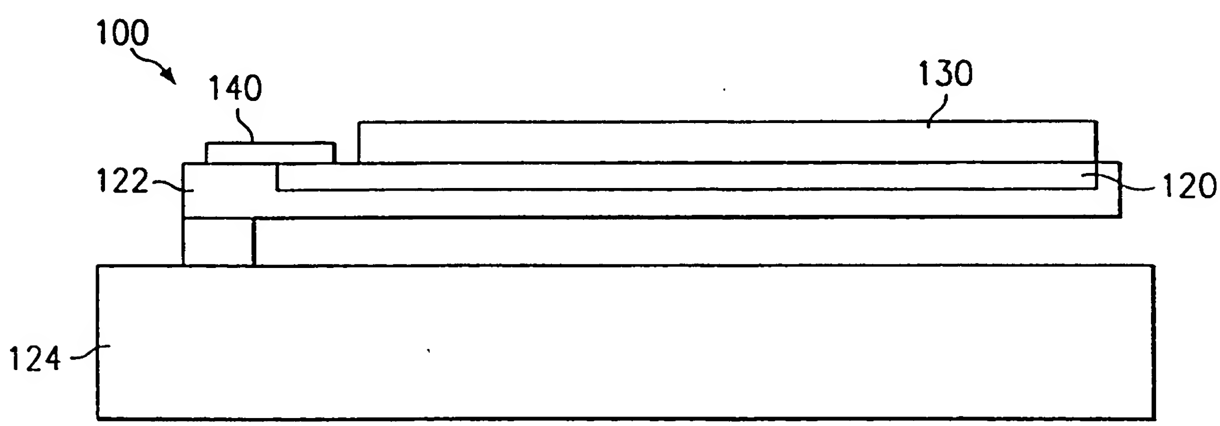
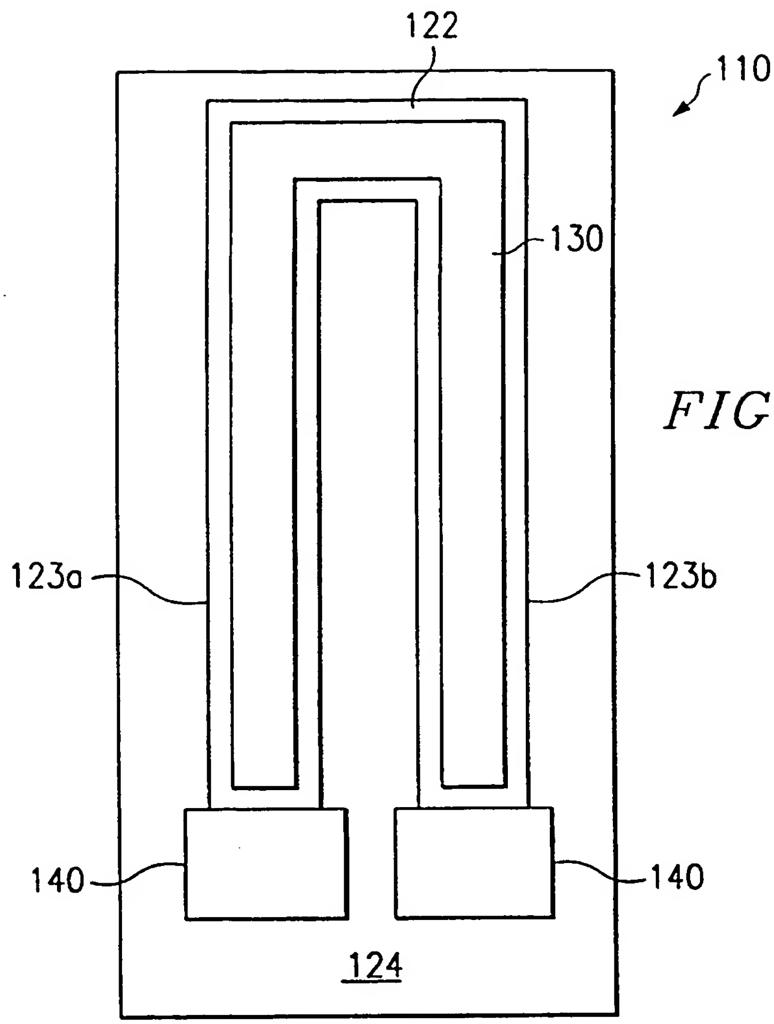


FIG. 3


122
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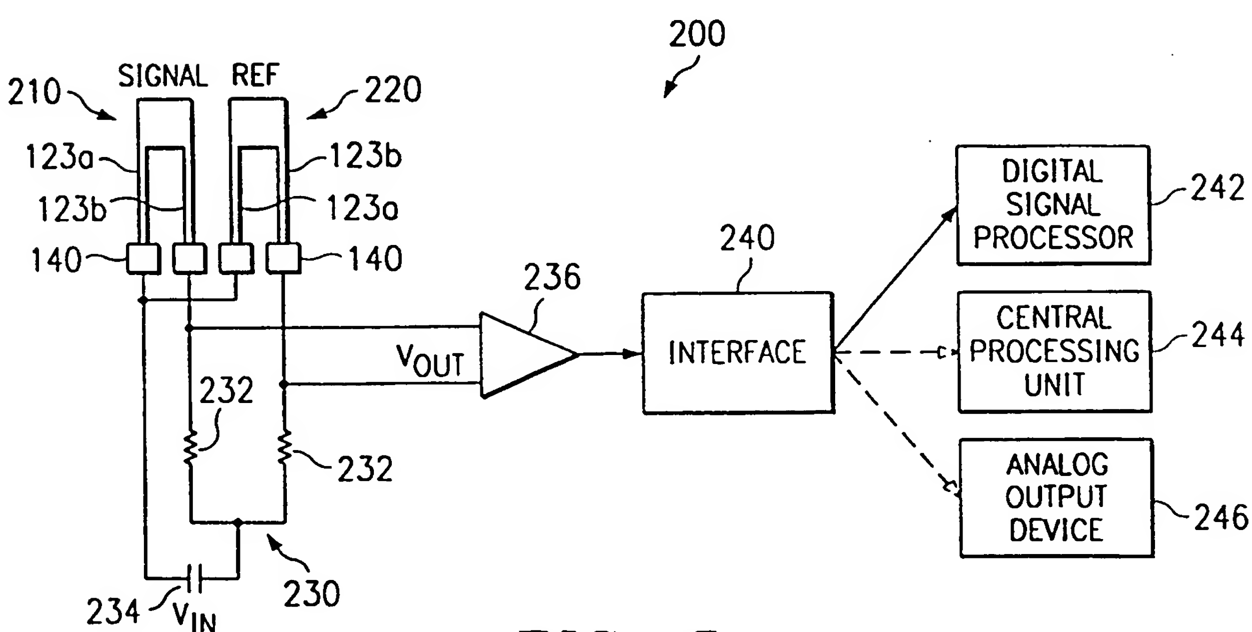
123a
123b
140
140
124

FIG. 4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123b
123b
123a
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236
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CENTRAL PROCESSING UNIT
244
ANALOG OUTPUT DEVICE
246
232
232
230
234
V_{IN}

FIG. 5